EPJ manuscript No.
(will be inserted by the editor)

Muon capture on the proton and deuteron

Frederick Gray[1,a] for the MuCap [1] and MuSun [2] Collaborations
[1]Department of Physics, Regis University, 3333 Regis Blvd., Denver, CO 80221, U.S.A.

Abstract. By measuring the lifetime of the negative muon in pure protium (^{1}H), the MuCap experiment determines the rate of muon capture on the proton, from which the proton's pseudoscalar coupling g_p may be inferred. A precision of 15% for g_p has been published; this is a step along the way to a goal of 7%. This coupling can be calculated precisely from heavy baryon chiral perturbation theory and therefore permits a test of QCD's chiral symmetry. Meanwhile, the MuSun experiment is in its final design stage; it will measure the rate of muon capture on the deuteron using a similar technique. This process can be related through pionless effective field theory and chiral perturbation theory to other two-nucleon reactions of astrophysical interest, including proton-proton fusion and deuteron breakup.

1 Introduction

Muon capture on the proton,

$$\mu^- + p \to \nu_\mu + n \ , \tag{1}$$

is a fundamental hadronic weak-interaction process. By measuring the rate at which it occurs, one can constrain the rich structure of the proton that arises from the interactions of quarks and gluons within it. On the other hand, muon capture on the deuteron,

$$\mu^- + d \to \nu_\mu + n + n \ , \tag{2}$$

is among the simplest two-nucleon processes, and can therefore contribute to the understanding of similar interactions. Notably, it may be connected to the fusion reaction $p + p \to d + e^+ + \nu_e$ that fuels stars (including our sun) and to the deuteron breakup reactions used by the Sudbury Neutrino Observatory to study neutrino oscillations.

Theoretical calculations that reflect the chiral symmetry of quantum chromodynamics (QCD) have been developed to describe processes 1 and 2. These calculations have reached impressive levels of precision, and they await experimental input that the MuCap and MuSun collaborations will soon provide.

2 Muon capture on the proton: theoretical motivation

Muon capture arises from the interaction between a leptonic current (representing the muon's transformation into its neutrino) and a hadronic current (the proton's transformation into a neutron). The hadronic current may be parameterized by writing down terms with all possible

[a] e-mail: `fgray@regis.edu`

Lorentz-invariant symmetry properties:

$$J_\alpha = g_v(q^2)\gamma_\alpha - g_a(q^2)\gamma_\alpha\gamma_5 + g_m(q^2)\frac{i}{2m_N}\sigma_{\alpha\beta}q^\beta - g_t(q^2)\frac{i}{2m_N}\sigma_{\alpha\beta}q^\beta\gamma_5 + g_s(q^2)\frac{1}{m_\mu}q_\alpha - g_p(q^2)\frac{1}{m_\mu}q_\alpha\gamma_5 \ . \tag{3}$$

In this expression, the terms correspond to vector, axial vector, weak magnetic, tensor, scalar, and pseudoscalar components. Our interest is in the pseudoscalar part. Fortunately, the others are either well-determined experimentally (g_v, g_a, and g_m) or can be shown theoretically to be zero by a G-parity symmetry argument (the "second class" currents g_t and g_s). Therefore, a measurement of the rate of muon capture at rest in protium is effectively a measurement of g_p at the fixed $q^2 = -0.88m_\mu^2$ that corresponds to the kinematics of the process.

An effective field theory (EFT) approach to low-energy phenomena parameterizes the higher-energy physics that has been abstracted from the theory as a set of low-energy constants. It then proceeds with a series expansion in a small parameter Q/Λ to describe phenomenological observables. With zero quark masses, the QCD Lagrangian is chirally symmetric: that is, the left- and right-handed components of the Dirac spinor are treated identically. This symmetry is spontaneously broken by the addition of nonzero quark mass terms. Heavy baryon chiral perturbation theory, an EFT that expands in both the pion (or light quark) mass and the coupling constant, takes advantage of this near-symmetry of the QCD. It leads to a theoretical prediction [3] for g_p:

$$g_p(q^2) = \frac{2m_\mu g_{\pi NN}(q^2)F_\pi}{m_\pi^2 - q^2} - \frac{1}{3}g_A(0)m_\mu m_N r_A^2 \tag{4}$$

which becomes 8.26 ± 0.23 when evaluated at the characteristic q^2 for muon capture. This result agrees with earlier results based on the partially conserved axial current (PCAC) and current algebra [4]. Thus, a fundamental symmetry of the Standard Model predicts g_p with a precision of 3%.

3 Muon capture on the proton: experimental status

Meanwhile, the precise theoretical prediction for g_p has long eluded an equally precise experimental check. The final state of muon capture contains no charged particles, so it is difficult to reliably detect directly. Experiments using neutron detection for muons stopped in a hydrogen gas target (performed in the late 1960s and early 1970s) achieved precisions of 9% [5] and 13% [6] for the capture rate.

Several more recent experiments have measured the muon capture rate by other techniques. The Saclay ordinary muon capture measurement [7] compared the apparent lifetime τ_{μ^-} of the negative muon to the lifetime τ_{μ^+} of the positive muon. The negative muon can decay ($\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$) or it can be captured, whereas positive muons can only decay. Attributing the additional part of the disappearance rate to the capture process, one obtains for the capture rate

$$\Lambda_S = \lambda_{\mu^-} - \lambda_{\mu^+} = \frac{1}{\tau_{\mu^-}} - \frac{1}{\tau_{\mu^+}} \ . \tag{5}$$

The TRIUMF radiative muon capture measurement [8] counted the photons emitted in the rare process $\mu^- + p \to \nu_\mu + n + \gamma$. However, both of these experiments were problematic because of the high density of the liquid hydrogen targets that they employed. In such targets, the atomic and molecular kinetics of the muon-proton system become very important. After a negative muon slows down through multiple scattering, it becomes electromagnetically bound to a proton, forming a muonic hydrogen atom. Such an atom behaves in many respects like ordinary hydrogen, but with a binding radius that is reduced by $m_\mu/m_e \approx 207$. Initially, the singlet and triplet atomic hyperfine states are statistically filled, but the triplet state is very

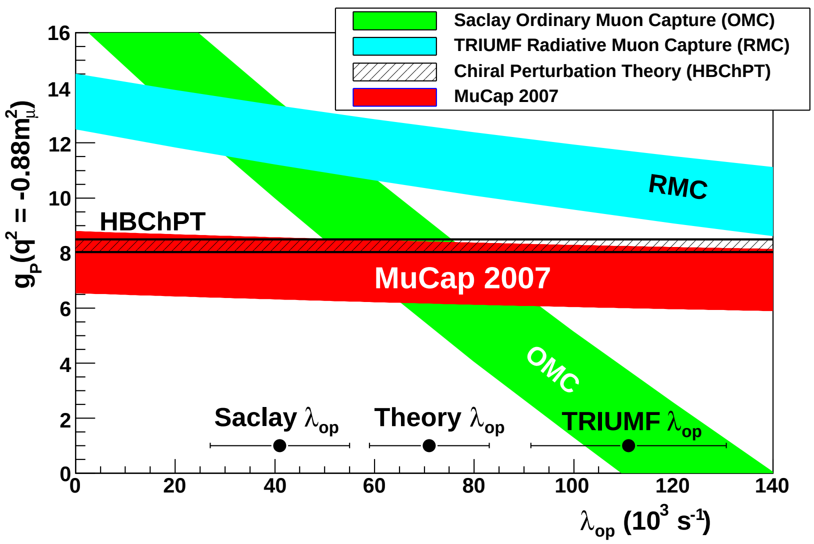

Fig. 1. The proton's pseudoscalar coupling g_p inferred from the observed capture rate in the previous generation of experiments (green and cyan bands) depends strongly on the ortho-para transition rate λ_{OP}. The MuCap experiment (red band) reduces this dependence substantially by using a low-density gas target, thereby confirming the heavy baryon chiral perturbation theory prediction (hatched band).

quickly depopulated through collisions with hydrogen molecules. It is from the resulting pure atomic singlet state that we intend to measure the nuclear muon capture rate Λ_S. However, at a rate of $\lambda_{of} \approx 2 \times 10^6$ s^{-1}, muonic hydrogen molecules ($p - \mu - p$) are formed. Initially, nearly all are in the ortho-molecular ($J = 1$) state; over time, the population shifts to the para-molecular ($J = 0$) state at a rate given by λ_{OP}. This parameter is very poorly-known; independent measurements [9,10] (shown in Figure 1) have given substantially inconsistent results, and neither experiment agrees with the theoretical calculation [11]. The large uncertainty associated with λ_{OP} makes it difficult to extract g_p from the results of either the Saclay or the TRIUMF experiment.

The MuCap experiment, performed using a muon beam from the high-intensity 590 MeV proton cyclotron at the Paul Scherrer Institute, uses a protium (isotopically pure ^{1}H) gas target whose density is ϕ =1% times that of liquid hydrogen. At room temperature, this density corresponds to 10 bar pressure. Both the molecular formation rate and the ortho-para transition rate are proportional to ϕ, so the dependence on the unknown λ_{OP} parameter is dramatically suppressed. In MuCap, 96% of the capture events come from the desired atomic singlet state. The basic experimental technique is a disappearance rate measurement similar to that used in the Saclay experiment, described by Equation 5. Under these conditions, the probability that a muon will be captured is approximately 0.16%. However, the low density introduces a new complication: a significant number of the incident muons actually stop outside the target gas, so an essential aspect of the experiment is to track each muon and include only those that can be proven to have stopped in hydrogen. For this reason, the target gas constitutes the active medium of a time projection chamber (TPC) that records the muon's ionization tracks. The deposited charge drifts vertically at a speed of 5.5 mm/μs in an applied electric field of 2 kV/cm, so the vertical coordinate of the track may be determined by its arrival time at the readout grid at the bottom. The sensitive volume of the TPC measures $15 \times 12 \times 28$ cm^3; a Bragg peak is clearly visible at the end of the track, and its three-dimensional coordinates are required to fall at least 1.5 cm from any boundary. As shown in Figure 2, the TPC is surrounded by a set of detectors (proportional chambers and scintillators) that track the electrons from muon decay. The disappearance rate is determined by a χ^2 minimization of an exponential function (plus a constant background term) relative to the spectrum of muon decay times.

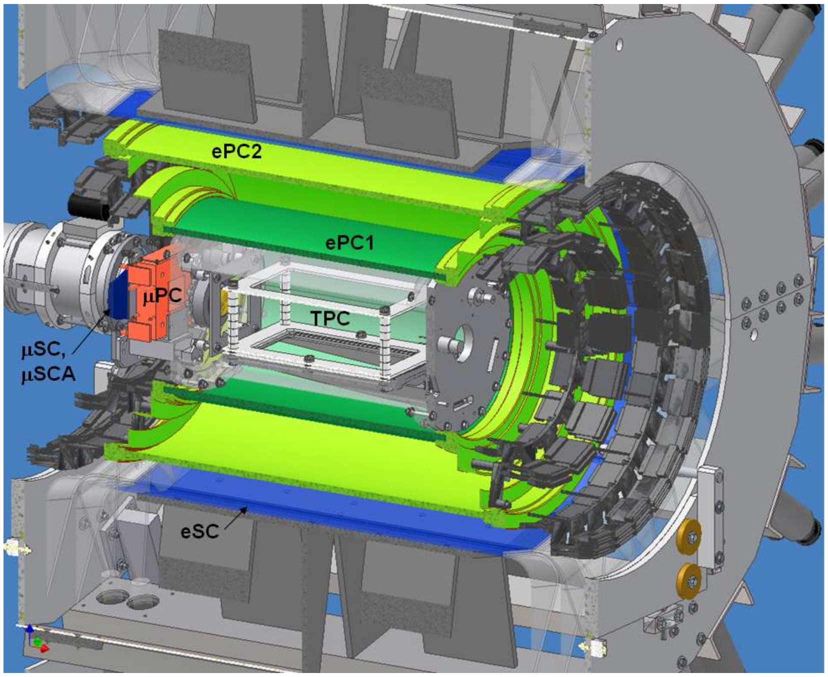

Fig. 2. The MuCap apparatus stops muons in a 10 bar protium environment, where the fiducial volume is surrounded by a time-projection chamber (TPC) that determines the muon stopping point. Electrons from muon decay within the hydrogen are detected by the surrounding cylindrical layers of proportional chambers (ePC1 and ePC2) and plastic scintillator (eSC).

The MuCap collaboration recently reported a first measurement [12] of the muon disappearance rate $\lambda_{\mu^-} = 455\,887.2 \pm 16.8\ \mathrm{s}^{-1}$. To extract Λ_S, the positive muon lifetime is taken from the MuLan experiment, which performed by a partially overlapping collaboration and using the same beamline at PSI as MuCap. An 11 part-per-million (ppm) result for the lifetime of $\tau_{\mu+} = 2.197\,013(21)(11)\ \mu\mathrm{s}$ has been published [13], with the intention to reach 1 ppm based on data already collected. The value agrees well with a measurement made within the MuCap apparatus as a consistency check, which gave $\tau_{\mu+} = 2.197\,01(14)\ \mu\mathrm{s}$. When these results are combined, the ensuing value for the capture rate is $725.0 \pm 17.4\ \mathrm{s}^{-}1$. From this value, $g_p(q^2 = -0.88m_\mu^2) = 7.3 \pm 1.1$ may be computed, once newly-computed radiative corrections [14] are taken into account. Within this 15% precision, the prediction of HBχPT is confirmed, thereby resolving a longstanding puzzle of nuclear physics.

The purity of the hydrogen target gas is critical for this measurement; since muon capture rates tend to scale as Z^4, a small impurity concentration can lead to a large change in the total disappearance rate. The experiment is fabricated from intrinsically clean, low-outgassing materials; notably, the frame of the TPC is made from Borofloat glass so that the chamber can be baked to 115° C without damage. The gas is initially filled into the system through a palladium-foil filter. It is then continuously circulated through a cooled Zeolite absorber system [15] that was demonstrated to reduce the concentrations of N_2 and O_2 to less than 7 parts per billion (ppb) and the concentration of H_2O vapor to 18-30 ppb. During the experiment, the yield of muon capture on impurity nuclei was monitored in real time by the unique signature of recoiling nuclei in the TPC data. Impurity-doped runs were collected in order to confirm the effect on the disappearance rate, and an appropriate correction was applied.

The protium gas used in MuCap must also be substantially depleted of deuterium. The scattering cross section for a muon-deuteron atom in protium gas has a Ramsauer-Townsend minimum at 1.6 eV, so any muon-deuteron atoms that might be formed tend to diffuse long distances through the target gas. This process represents a time-dependent loss of muons from

the fiducial volume of the TPC, which in turn distorts the muon disappearance spectrum. Accelerator mass spectroscopy (AMS) measurements [16] have confirmed that the hydrogen used in the published data set, which was produced by electrolysis of deuterium-depleted water purchased from Ontario Power Generation, had a deuterium content of 1.44 ± 0.13 ppm. This level agrees well with the dependence of the muon disappearance rate on the observed impact parameter between the muon stopping point and the electron track. Again, dedicated runs with a deuterium-doped target allowed an appropriate correction to be made.

The published MuCap result is based on the analysis of 1.6×10^9 stopped muon decays observed in the summer 2004 running period. This represents less than 10% of the full MuCap data set, which is anticipated to give a final precision of 7% for g_p. The rate at which muons could be stopped was substantially enhanced by the MuLan kicker [17], which allows "Muon on Demand" operation. For 25 μs after an entering muon has been detected, the beamline is closed off by the application of a $\sim$1.6 kV/cm electric field along a 1.5 m segment upstream from the detector. This time structure allows efficient operation by eliminating "pile-up" of muons within the TPC; each muon typically arrives just as the ionization charge deposited by its predecessor has been cleared from the chamber. The other substantial improvement in the experiment was to the purity of the target gas: a cryogenic isotope separation was performed, leading to a deuterium concentration less than 0.006 ppm (a conservative upper limit based on AMS results) in the hydrogen that was used for the forthcoming data.

4 Muon capture on the deuteron

Muon capture on the deuteron is a member of a family of interesting reactions; other members include proton-proton fusion ($p + p \to d + e^+ + \nu_e$) and the charged and neutral current deuteron breakup reactions ($\nu_x + d \to p + n + \nu_x$ and $\nu_e + d \to n + n + e^-$). Each of these is a semileptonic two-nucleon interaction that either forms or destroys a deuteron. The fusion process drives energy production in stars, while the deuteron breakup processes are used by the Sudbury Neutrino Observatory to monitor the flux of solar neutrinos [18]. Consequently, an improved understanding of the cross-sections for these reactions will have substantial astrophysical implications. A new proposal [19] to measure the rate of muon capture on the deuteron has been submitted to PSI and has received approval; the experiment will be known as MuSun.

The connections among these processes are often discussed in terms of a *pionless* EFT, which treats the pion as a high-energy particle to be integrated into the low-energy constants (LECs). The set of LECs consists of many that are well-known from one-nucleon processes, plus a new constant L_{1A} that describes the two-nucleon weak axial current. The determination of L_{1A} with by far the smallest stated uncertainty is 4.2 ± 0.1 fm^3 from the rate of tritium beta decay ([20] as interpreted by [21]). However, because the triton is a three-nucleon system, this calculation may introduce a significant model dependence. Other relevant techniques include reactor $\bar{\nu} + d$ scattering experiments [22] ($L_{1A} = 3.6 \pm 5.5$ fm^3), self-consistency of the solar neutrino data [21] ($L_{1A} = 4.0 \pm 6.3$ fm^3), and helioseismology [23] ($L_{1A} = 4.8 \pm 6.7$ fm^3). It should be noted that, in all of these cases, the stated uncertainty is larger than the measured value itself. In contrast, the MuSun experiment proposes to measure L_{1A} with an uncertainty of ± 1.25 fm^3.

The pionless EFT calculation is in principle only valid for low-energy processes, where the momentum scale $Q << m_\pi$. However, for muon capture, $Q = 102.1$ MeV $\approx m_\pi$, so this theory is not clearly appropriate. Indeed, a component of the capture rate involves the emission of neutrons at energies up to $Q/2 = 51$ MeV. This part would not be described well by the pionless model, as it would necessarily include meson exchange currents. Consequently, chiral perturbation theory is also applied [24] to study muon capture on the deuteron. In this theory, the LEC that describes the two-nucleon axial current is known as $\hat{d}^R$. The MuSun data will also constrain this parameter.

MuSun will reuse a substantial amount of equipment and expertise from the MuCap experiment; the basic disappearance method technique will remain essentially unchanged, as will the electron detector system. The most significant changes to the experiment arise from the different kinetics of the muon-deuteron system relative to the muon-proton system. The deuteron

has spin 1, so the allowed total-spin states for the muonic atom are the doublet ($J = 1/2$) and the quartet ($J = 3/2$). Initially, these states are populated statistically, with 2/3 of the atoms in the quartet state. The desired measurement is from a pure atomic doublet state; unfortunately, the quartet-to-doublet transition rate λ_{qd} is not sufficient to reach this state quickly (relative to the muon lifetime) at density ϕ =1%. A higher density is needed to accelerate the spin-flip transition. However, this increased density also increases the rate of $d - \mu - d$ molecular formation to an undesirable level; to compensate for this effect, we must reduce the temperature. The optimal target conditions appear to be a density $\phi = 5\%$ with a temperature $T = 30$ K (rather than room temperature). Consequently, a cryogenic gas target system and a TPC that is able to operate under these conditions are required. A preliminary design for the chamber uses a pad plane approach; studies are in progress to determine its ideal geometry.

Neutron detector systems will be employed to observe both fusion ($d+d+\mu^- \to {}^3\mathrm{He}+n+\mu^-$) and capture ($\mu^- + d \to n + n + \nu_\mu$) neutrons. These two processes may be separated based on the neutron energy: all fusion electrons have a kinetic energy of 2.45 MeV, while some capture neutrons reach as high as 53 MeV. The fusion process is a sentinel of molecular formation; by monitoring these rates as a function of time after the muon stops, the calculated atomic and molecular kinetics can be verified.

A staged strategy has been formulated for the implementation of the MuSun experiment. In 2008, a prototype of the new TPC will be constructed and operated at room temperature in the muon beam at PSI, with the engineering goal of demonstrating the performance of its pad geometry. Important studies of systematic errors related to gas impurities will also take place, along with a measurement of the residual polarization of the muon-deuteron atom. By late 2009, the TPC should be ready for cryogenic operation, and it is anticipated that the production data will be accumulated in 30 weeks of beam time over a two-year period. A total of 1.8×10^{10} negative muon decays will be observed. The positive muon lifetime will also be measured as a instrumental check in the new apparatus, requiring 1.2×10^{10} positive muon decays to give similar precision.

The author would like to thank his colleagues in the MuCap and MuSun collaborations for their support, as well as the organizers of the 2007 Advanced Studies Institute on Symmetries and Spin for an enjoyable meeting. Summer travel funds (for which the author is particularly grateful) were provided by a National Science Foundation Research Opportunity Award supplement through the University of Illinois at Urbana-Champaign.

References

1. MuCap Collaboration: V.A. Andreev, B. Besymjannykh, A.A. Fetisov, V.A. Ganzha, V.I. Jatsoura, P.A. Kravtsov, A.G. Krivshich, M. Levchenko, E.M. Maev, O.E. Maev, G.E. Petrov, G.N. Schapkin, G.G. Semenchuk, M.A. Soroka, V. Trofimov, A.A. Vasilyev, A.A. Vorobyov, M.E. Vznuzdaev (Petersburg Nuclear Physics Institute, Gatchina, Russia); P.U. Dick, A. Dijksman, J. Egger, D. Fahrni, M. Hildebrandt, A. Hofer, L. Meier, C. Petitjean, R. Schmidt (Paul Scherrer Institut, Villigen, Switzerland); T. Banks, T.A. Case, K.M. Crowe, S.J. Freedman, F.E. Gray, B. Lauss (University of California, Berkeley, CA, U.S.A.); D.B. Chitwood, S. Clayton, P. Debevec, D.W. Hertzog, P. Kammel, B. Kiburg, S. Knaack, R. McNabb, F. Mulhauser, C.S. Özben, D. Webber, P. Winter (University of Illinois at Urbana-Champaign, IL, U.S.A.); L. Bonnet, J. Deutsch, J. Govaerts, D. Michotte, R. Prieels (Université Catholique de Louvain, Belgium); R.M. Carey, K.R. Lynch (Boston University, Boston, MA, U.S.A.); T. Gorringe, V. Tishchenko (University of Kentucky, Lexington, KY, U.S.A.).
2. MuSun Collaboration: V.A. Andreev, V.A. Ganzha, P.A. Kravtsov, A.G. Krivshich, M. Levchenko, E.M. Maev, O.E. Maev, G.E. Petrov, G.N. Schapkin, G.G. Semenchuk, M.A. Soroka, A.A. Vasilyev, A.A. Vorobyov, M.E. Vznuzdaev (Petersburg Nuclear Physics Institute, Gatchina, Russia); D.W. Hertzog, P. Kammel, B. Kiburg, S. Knaack, F. Mulhauser, P. Winter (University of Illinois at Urbana-Champaign, IL, U.S.A.); M. Hildebrandt, B. Lauss, C. Petitjean (Paul Scherrer Institut, Villigen, Switzerland); T. Gorringe, V. Tishchenko (University of Kentucky, Lexington, KY, U.S.A.); R.M. Carey, K.R. Lynch (Boston University, Boston, MA, U.S.A.); R. Prieels (Université

Catholique de Louvain, Belgium); F.E. Gray (Regis University, Denver, CO, U.S.A.); A. Gardestig, K. Kubodera, F. Myhrer (University of South Carolina, Columbia, SC, U.S.A.).
3. V. Bernard, N. Kaiser, U.G. Meissner, Int. J. Mod. Phys. **E4**, 193 (1995)
4. T. Gorringe, H.W. Fearing, Rev. Mod. Phys. **76**, 31 (2004)
5. A. Alberigi Quaranta et al., Phys. Rev. **177**, 2118 (1969)
6. V.M. Bystritsky et al., Zh. Eksp. Teor. Fiz. **66**, 43 (1974), Sov. Phys. JETP **39**, 19 (1974)
7. G. Bardin et al., Nucl. Phys. **A352**, 365 (1981)
8. D.H. Wright et al., Phys. Rev. **C57**, 373 (1998)
9. G. Bardin et al., Phys. Lett. **B104**, 320 (1981)
10. J.H.D. Clark et al., Phys. Rev. Lett. **96**, 073401 (2006)
11. D.D. Bakalov, M.P. Faifman, L.I. Ponomarev, S.I. Vinitsky, Nucl. Phys. **A384**, 302 (1982)
12. V.A. Andreev et al. (MuCap Collaboration), Phys. Rev. Lett. **99**, 032002 (2007)
13. D.B. Chitwood et al. (MuLan Collaboration), Phys. Rev. Lett. **99**, 032001 (2007)
14. A. Czarnecki, W.J. Marciano, A. Sirlin, Phys. Rev. Lett. **99**, 032003 (2007)
15. V.A. Ganzha et al., Nucl. Instrum. Meth. **A578**, 485 (2007)
16. H.A. Synal, M. Stocker, M. Suter, Nucl. Instr. Meth. **B259**, 7 (2007)
17. M.J. Barnes, G.D. Wait, IEEE Transactions on Plasma Science **32**, 1932 (2004)
18. B. Aharmim et al. (Sudbury Neutrino Observatory Collaboration), Phys. Rev. **C75**, 045502 (2007)
19. V.A. Andreev et al. (MuSun Collaboration), *Muon capture on the deuteron: the MuSun experiment*, http://www.npl.uiuc.edu/exp/musun/documents/prop07.pdf
20. R. Schiavilla et al., Phys. Rev. **C58**, 1263 (1998)
21. J.W. Chen, K.M. Heeger, R.G.H. Robertson, Phys. Rev. **C67**, 025801 (2003)
22. M. Butler, J.W. Chen, P. Vogel, Phys. Lett. **B549**, 26 (2002)
23. K.I.T. Brown, M.N. Butler, D.B. Guenther (2002), `nucl-th/0207008`
24. S. Ando, T.S. Park, K. Kubodera, F. Myhrer, Phys. Lett. **B533**, 25 (2002)